The onset of exciton absorption in modulation doped GaAs quantum wells

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Abstract

We study the evolution of the absorption spectrum of a modulation doped GaAs/AlGaAs semiconductor quantum well with decreasing the carrier density. We find that there is a critical density which marks the transition from a Fermi edge singularity to a hydrogen-like behavior. At this density both the lineshape and the transitions energies of the excitons change. We study the density dependence of the singularity exponent α and show that disorder plays an important role in determining the energy scale over which it grows.
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The absorption spectrum in the presence of a Fermi sea of electrons has been a subject of theoretical and experimental research for more than three decades. The interest in this problem was triggered by the pioneering work of Mahan [1], who showed that in metals and bulk semiconductors this spectrum should exhibit a power law singularity at the Fermi energy. This singularity, which became known as the Fermi edge singularity (FES), reflects the response of the Fermi sea electrons to the attractive potential of the valence band hole. Mahan's work was followed by a bulk of theoretical works, which established the many body nature of the FES and provided the tools to treat it [2].

The FES was indeed observed in the X-ray absorption of metals but was never observed in bulk semiconductors. Its first observation in semiconductors was in modulation doped quantum wells. It is manifested in these systems as a pronounced enhancement of the absorption at the Fermi edge, with an asymmetrical lineshape: a fast rise at the low energy side and a slow fall at high energies. A signature of the FES is its strong dependence on temperature and electron density. The high energy slope becomes more and more gradual when these parameters are increased [3–5].

An intriguing aspect of the behavior of a system of many electrons and a hole is the existence of a bound state. Initially, the singularity was associated with a bound state (the so-called Mahan exciton), which is built out of empty conduction band states below the Fermi level, but soon after, it was realized that this exciton is unstable [2]. Nevertheless, a bound state of electrons and a hole should exist in a two-dimensional (2D) system. It is well known that in 2D bound states occur for arbitrarily small attractive potentials. Thus, the attractive potential of a valence hole should have a bound state even after the many-body interactions have been accounted for.

The recent discovery of the charged exciton, X^-, in semiconductor quantum wells, at low-electron densities [6,7] created a renewed interest in the problem. The X^-, which consists of two electrons with opposite spins bound to a valence band hole, appears at the absorption and emission spectra as a spectral line at some energy below the neutral exciton line, X. A natural question which then arises is how does the low density spectrum, of the X^- and

X bound states, transform into the FES. This issue has been addressed in a number of theoretical publications [8,9]. It was shown that an X^- like bound state should persist to a high electron density, and be manifested in the absorption spectrum as a spectral line with an asymmetric singular shape of the form $(\omega - \omega_0)^{-\alpha}$. Another singular peak, which is exciton like, was predicted to appear at some energy above that line. Indeed, this prediction was recently confirmed in CdTe modulation doped quantum wells [10], where the X-X^- doublet was observed up to densities of a few$\times 10^{11}$ cm^{-2}. Attempts to observe the X-X^- doublet in the absorption spectrum of GaAs quantum wells in the presence of a high density two-dimensional electron gas (2DEG) have yielded inconclusive results [5].

In this paper we investigate the evolution of the absorption spectrum of a single GaAs/AlGaAs quantum well with decreasing electron density, from 1.5×10^{11} to 1.5×10^{10} cm^{-2}. We tune the electron density continuously by applying a voltage to a semi-transparent gate relative to an ohmic contact, which is made into the 2DEG. We find that there is a critical density which marks the transition from a FES to a hydrogen-like behavior. At this critical density both the lineshape and the transitions energies of the excitons exhibit a clear change: the singular asymmetric line becomes a symmetric resonance and the energy difference between X and X^- becomes constant. We study the density dependence of the singularity exponent α and show that the energy scale over which it grows is determined by disorder.

The absorption spectrum is obtained using photocurrent spectroscopy. Electrons are excited from surface states by the incident photons to energies above the Schottkey barrier, and then drift into the doped region. From there they tunnel into the well and are collected by the ohmic contacts of the 2DEG, giving rise to a photocurrent in the gate circuit. This mechanism gives rise to a photocurrent at photon energies which extend well below the GaAs gap. At photon energies which can be absorbed in the quantum well there is an additional contribution to the photocurrent, resulting from electron-hole pairs created in the well. The characteristics of this photocurrent will be discussed in details elsewhere. There are, however, two important experimental points which should be mentioned:

- In this gated structures light illumination gives rise to some depletion of the carrier density. However, since the capacitance of the structure is constant, this only implies that we need to add some positive gate voltage in order to recover the density in the dark. We have verified this behavior over a large light intensity range.

- The photocurrent from the quantum well rides on a background signal, due to surface state absorption. The value of this background photocurrent depends on the sample structure and surface treatment. The spectra are displayed after this background was subtracted.

The sample structure that we investigated consists of the following sequence of layers: a 300 nm-thick GaAs buffer, a superlattice with 50 periods of 100 nm $Al_{0.37}Ga_{0.67}As$ and 30 nm GaAs , a 20 nm-thick GaAs quantum well, a 50 nm-thick $Al_{0.37}Ga_{0.67}As$ spacer layer, Si delta-doping of 1×10^{12} cm^{-2}, a 100 nm $Al_{0.37}Ga_{0.67}As$, a 20 nm thick n-type $Al_{0.37}Ga_{0.67}As$, and a GaAs cap layer. The wafer is processed into a field-effect transistor structure, with a 5 nm thick semi-transparent PaAu gate. Determination of the electron density N under illumination is done by measuring the photoluminescence (PL) spectrum as a function of magnetic field, and finding the magnetic field values at which an integer number of Landau levels are filled. At these magnetic fields there is an abrupt change in the PL spectrum [11]. This procedure works well up to $N \sim 8 \times 10^{10}$ cm^{-2}. To obtain the lower electron densities we use the capacitance of this structure to extrapolate the curve of $N(V_g)$, where V_g is the gate voltage.

The measurements are conducted in a liquid helium storage dewar at a temperature of 4.2 K, using an optical fiber based system. We use a single-mode fiber at close proximity, ~ 100 μm, to illuminate the sample. A second multi-mode fiber is set at a distance of a few mm from the sample and collects the emitted PL. The sample is excited by a tunable Ti-sapphire laser, which is coupled into the single-mode fiber. The photocurrent is amplified by a sensitive current amplifier and measured using a lock-in amplifier. We have conducted the measurements using power levels from 10 nW to 1 mW. Except for a shift in the $N(V_g)$ curve and some broadening at high power levels the results are power independent. After an absorption measurement at a given gate voltage V_g, the laser is set to 1.541 eV and the

PL is measured.

Figure 1 shows a set of photocurrent and emission spectra taken for various gate voltages. We label each spectrum with the corresponding Fermi energy $E_F = \pi\hbar^2 N/m^*$, where N is the electron density and m^* is the electron effective mass ($m^* = 0.067m_0$). At large electron densities (Figs. 1a) the absorption edge is a broad step which is shifted to high energies relative to the emission. In Fig. 1b, which is taken at $E_F = 2.5$ meV, we observe the formation of two broad peaks: one at the absorption edge and the other a few meV higher. As the density is further reduced ($E_F < 1.1$ meV) the two broad peaks acquire an asymmetric singular lineshape, characterized by a steep rise at low energies and a slow fall at high energies (Fig. 1c-d). Following the notation of Ref. [8–10] we label the low energy peak as ω_1 and the high energy one as ω_2. The singularity in ω_2 increases very fast, and at $E_F = 0.75$ meV it becomes a symmetric resonance, the heavy-hole exciton (Fig. 1e). The ω_1 peak exhibits less pronounced changes. As the density is reduced it becomes weaker and evolves into the well known charged exciton, X^- (Figs. 1e-f). A replica of that scenario appears at the light-hole exciton energy, 4 meV higher.

The evolution of the singularity is surprisingly fast. Figure 2 describes a fit of a power law singularity $A(\omega) = (\omega - \omega_0)^{-\alpha}$ to the high side energy of ω_2 at $E_F = 0.9$ meV. Such a fitting procedure allows us to accurately extract the exponent α at each density. The inset shows the dependence of α on E_F. It is seen that α increases by nearly an order of magnitude (from 0.05 to 0.4) in a very narrow range, $\Delta E_F = 0.25$ meV, which corresponds to reducing the electron density by less than 1×10^{10} cm^{-2}.

The exponent α is related to the phase shift of the electrons at the Fermi surface, when scattering off the valence hole potential [9]. In that sense it measures the efficiency of the Fermi sea electrons in screening that potential: the smaller α is, the better is the screening. Previous studies have reported a significantly broader density range over which the singularity was observed [3–5,10]. For example, in Ref. [5] a similar change of α was observed on an energy scale of $\Delta E_F \sim 10$ meV, more than an order of magnitude larger than in our measurements. It was argued that the energy scale over which α changes is related

to the many body nature of the problem [5,9]. As we shall show in the following, disorder plays a critical role and determines the energy scale at which the singularity is observed.

Examining the PL spectra, we notice that at the density, at which α starts to grow the PL lineshape transforms from a broad single peak to two narrow resonances, associated with the X and X^-. This behavior of the PL was extensively studied by some of us [7,13]. We have shown that the appearance of excitons marks the onset of strong localization of the electrons in the potential fluctuations of the ionized donors. These donors, which are at a distance of 50 nm (the spacer width), are randomly distributed in the plane and induce a spatially fluctuating electrostatic potential at the 2DEG. At high electron density the 2DEG efficiently screens the fluctuations, but as the density is reduced the screening becomes less efficient and they grow considerably [14]. Thus, the growth of α is related to the onset of strong disorder in the sample.

It should be noticed that this sample is of high quality. This is evidenced by the high mobility ($\sim 10^6$ $cm^2V^{-1}s^{-1}$), the narrow exciton linewidth (0.3 meV), and the absence of a Stokes shift between the PL and absorption (< 0.1 meV) . Thus, at $E_F > 1.1$ meV, where the potential fluctuations are suppressed, our sample could be considered as close to ideal. Nevertheless, the singularity is significantly suppressed at that range. Only when disorder sets in, and electrons can not efficiently screen the valence-hole potential, α becomes large enough to make ω_2 and ω_1 observable as singular peaks. Indeed, it is indicated in Ref. [10] that there is strong disorder present in the samples and the mobility is rather low. Large disorder is also present in the narrow quantum wells studied in Ref. [5], as is evident by the very broad exciton line ~ 8 meV. The wide range in which singular lineshapes are observed in these works is, therefore, related to the large disorder in the samples which were used and not to a fundamental energy scale. The use of a gated sample in this study allows us to control the onset and amount of disorder.

Let us now turn to examining the density dependence of the energies of the ω_1 and ω_2 peaks (Fig. 3). The data is presented for a limited density range, where the singularity edge is clear and the peak energy can be unambiguously determined. In Fig. 3a we show

the ω_1 and ω_2 transition energies. It is seen that the ω_2 peak shifts to higher energies with increasing density while the energy of ω_1 remains nearly constant. In Fig. 3b we present the energy difference $\hbar(\omega_1 - \omega_2)$ as a function of E_F. It is evident that there exists a threshold density value, $N_c \approx 2.5 \times 10^{10}$ cm^{-2} (which corresponds to $E_F = 0.85$ meV), below which $\hbar(\omega_2 - \omega_1)$ is constant and equals 1.2 meV. Only above this threshold density the energy difference $\hbar(\omega_2 - \omega_1)$ grows. This behavior is in clear contrast with that reported in Ref. [10], where it was argued that $\hbar(\omega_2 - \omega_1)$ changes linearly with E_F, all the way to zero density. The value of 1.2 meV is well documented experimentally as the X^- binding energy in a 20 nm GaAs quantum well [7,12]. In fact, it is the energy difference between the two peaks in the PL spectra (Fig. 1). It should be emphasized that the optical spectra (Figs. 1e-f) clearly show that the density is indeed changing in this range, as evidenced by the exchange of oscillator strength between the X and the X^-. This conclusion is supported by transport measurements through the sample at this range, which show that the conductivity decreases as the gate voltage becomes more negative.

To explain this behavior let us consider the energy spectrum of the system [8], which is schematically shown at the inset of Fig. 3b (μ is the chemical potential and E_c is the single particle band gap). At the limit of infinitesimal density there are two bound states, X and X^-, at a relatively large energy distance (the exciton binding energy, E_X) below E_c. The energy separation between the two bound states is E_B, the X^- binding energy. On the other hand, at the limit of high electron density there is only one, X^--like, bound state. The absorption spectrum of the system was predicted to consist of two peaks, with an energy difference given by [8,9]

$$\hbar(\omega_2 - \omega_1) = \mu - \varepsilon_b \tag{1}$$

where ε_b is the binding energy of the X^- like bound state. It is important to note that both μ and ε_b in Eq. 1 are measured with respect to the same level, which we take as the bottom of the conduction band at zero electron density, E_c^0. Equation 1 has a simple meaning: it describes the energy cost for ionizing the X^--like bound state by exciting one of the two

electrons to the chemical potential level μ. However, it is clear that this relation is valid only at the high density limit. At low densities $\mu \sim 0$ and $\mid \varepsilon_{\rm b} \mid > {\rm E_X}$. Hence, Eq. 1 would imply that $\hbar(\omega_2 - \omega_1) > {\rm E_X}$, and that we should observe a huge increase in $\hbar(\omega_2 - \omega_1)$ below a certain density. Thus, the use of Eq. 1 down to zero density is incorrect [10], and consequently the determination of the X^- binding energy in CdTe has to be re-examined. Our experimental findings show that below $N_{\rm c}$ the correct relation is $\hbar(\omega_2 - \omega_1) = {\rm E_B}$. Only at large densities, where there is only one bound state, we are at the limit covered by Eq. 1.

It is remarkable that at the threshold density $N_{\rm c}$ the exciton lineshape undergoes a drastic change. This change is clearly seen in Fig. 1: the exciton lineshape is symmetric below $N_{\rm c}$ (Fig. 1e-f) and becomes a singular asymmetric line above it (Figs. 1b-d). The comparison between the exciton lineshape in Figs. 1e and 1d is particularly interesting. The difference is manifested not only in the high energy side but also at the low energy side, which becomes steeper above $N_{\rm c}$. The fact that both the energy dispersion and lineshape change at $N_{\rm c}$ implies that this density marks the transition from a hydrogen-like behavior to a FES. It is interesting to note that the value of $N_{\rm c}$, which is found here, is very close to that reported in electroreflectance measurements [12], where quenching of the excitonic absorption was studied.

Finally, we wish to comment on the behavior at high densities. It can be seen at Fig. 3b that at densities above $N_{\rm c}$ the energy separation between the X and X^- grows monotonically. The dashed line describes the relation $\hbar(\omega_2 - \omega_1) = {\rm E_B} + {\rm E_F}$, (where ${\rm E_B} = 1.2$ meV). This relation results from Eq. 1 and was used to fit the data in Ref. [10]. It is evident that all the measured points in Fig. 3b are below this curve, but as the density gets higher the data points are approaching the curve. Unfortunately, we can not determine the behavior accurately at the high density limit. The X and X^- lines become too broad, and one can not reliably obtain their energy separation. Nevertheless, it is obvious from our data at higher densities that the energy separation indeed increases monotonically with density.

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FIGURES

Fig. 1: A series of the absorption (solid line) and PL (dotted) spectra at several gate voltages. Each spectrum is labeled by the corresponding Fermi level, $E_F = \pi\hbar^2 N_s/m^*$. Each spectrum is displayed after subtraction of the background signal (see text) and is normalized by the intensity of the X peak.

Fig. 2: (a) A fit of the function $A(\omega) = (\omega - \omega_0)^{-\alpha}$ to the exciton singularity at $E_F = 0.9$ meV. (b) The dependence of the exponent α on E_F.

Fig. 3: (a) The energies of the X and X^- transitions as a function of E_F. (b) The solid circles describe the measured energy difference $\hbar(\omega_2 - \omega_1)$ as a function of E_F. The dashed line describes the relation $\hbar(\omega_1 - \omega_2) = 1.2 + E_F$. The inset shows the schematically the energy spectrum of the system as a function of density.

Figure 1, Yusa *et al.*

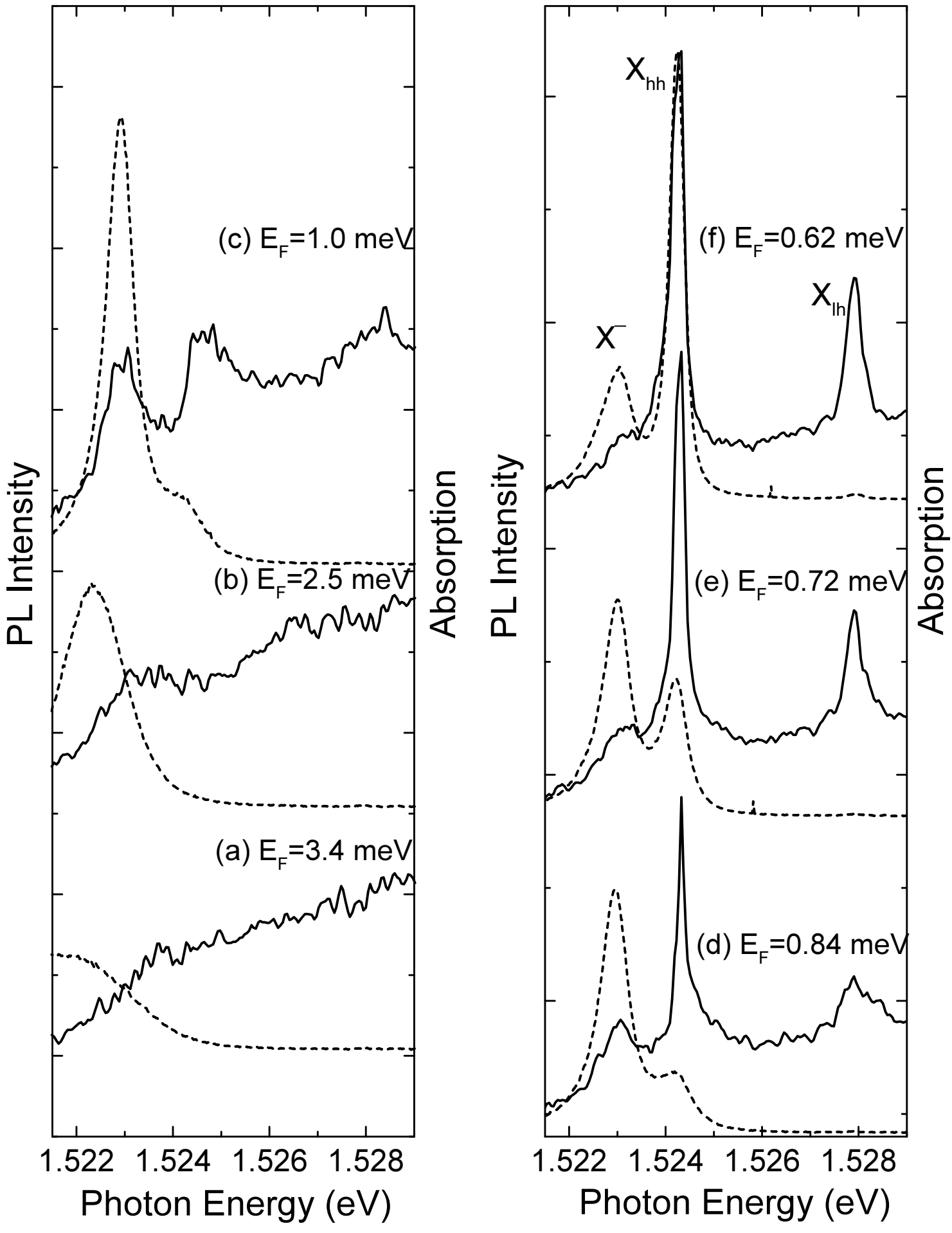

Figure 2, Yusa *et al.*

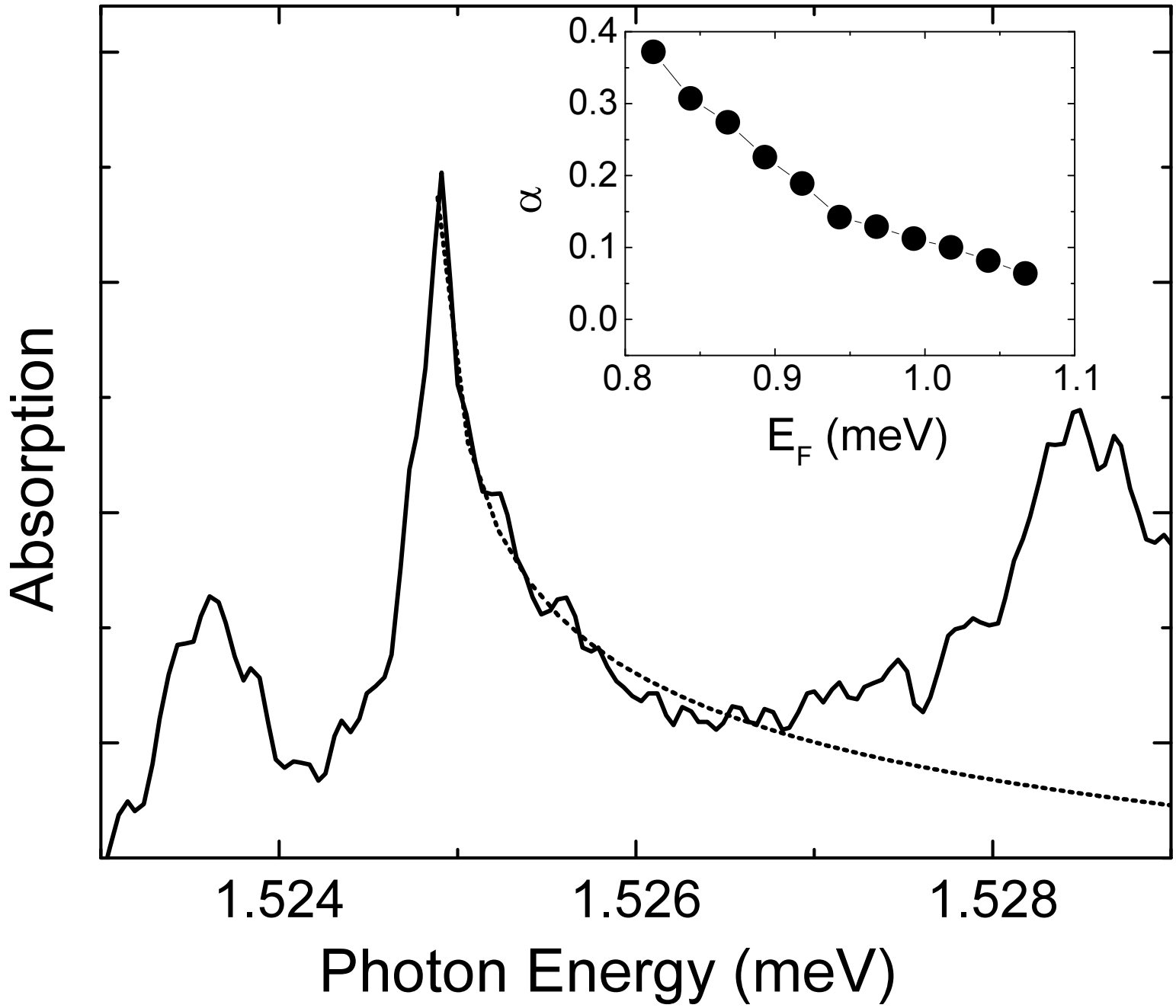

Figure 3, Yusa *et al.*